Description

DIELECTROPHORETIC DISPLAYS

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a non-provisional of Provisional Application Serial No. 60/419,019, filed October 16, 2002. This application is also a continuation-in-part of copending Application Serial No. 08/983,404, filed March 26, 1999, which is the United States National Phase of International Application No. PCT/US96/12000, filed July 19, 1996, which is itself a continuation-in-part of Application Serial No. 08/504,896, filed July 20, 1995 (now U.S. Patent No. 6,124,851). The entire disclosure of all the aforementioned applications, and of all U.S. patents and published applications mentioned below, is herein incorporated by reference.

BACKGROUND OF INVENTION

[0002] This invention relates to dielectrophoretic displays, and methods for operating such displays. More specifically, this invention relates to dielectrophoretic displays in which solid particles and a suspending fluid are held within a cavity.

[0003] Electrophoretic displays have been the subject of intense research and development for a number of years. Such displays use a display medium comprising a plurality of electrically charged particles suspended in a fluid. Electrodes are provided adjacent the display medium so that the charged particles can be moved through the fluid by applying an electric field to the medium. In one type of such electrophoretic display, the medium comprises a single type of particle having one optical characteristic in a fluid which has a different optical characteristic. In a second type of such electrophoretic display, the medium contains two different types of particles differing in at least one optical characteristic and in electrophoretic mobility; the particles may or may not bear charges of opposite polarity. The optical characteristic which is varied is typically color visible to the human eye, but may, alternatively or in addition, be any one of more of reflectivity, retroreflectivity, luminescence, fluorescence, phosphorescence, or (in the case of displays intended for machine reading) color in

the broader sense of meaning a difference in absorption or reflectance at non-visible wavelengths.

[0004] Electrophoretic displays can be divided into two main types, namely unencapsulated and encapsulated displays. In an unencapsulated electrophoretic display, the electrophoretic medium is present as a bulk liquid, typically in the form of a flat film of the liquid present between two parallel, spaced electrodes. Such unencapsulated displays typically have problems with their long-term image quality which have prevented their widespread usage. For example, particles that make up such electrophoretic displays tend to cluster and settle, resulting in inadequate service-life for these displays.

[0005] An encapsulated, electrophoretic display differs from an unencapsulated display in that the particle-containing fluid is not present as a bulk liquid but instead is confined within the walls of a large number of small capsules. Encapsulated displays typically do not suffer from the clustering and settling failure mode of traditional electrophoretic devices and provides further advantages, such as the ability to print or coat the display on a wide variety of flexible and rigid substrates.

[0006] For further details regarding encapsulated electrophoretic displays, the reader is referred to U.S. Patents Nos. 5,930,026; 5,961,804; 6,017,584; 6,067,185; 6,118,426; 6,120,588; 6,120,839; 6,124,851; 6,130,773; 6,130,774; 6,172,798; 6,177,921; 6,232,950; 6,249,721; 6,252,564; 6,262,706; 6,262,833; 6,300,932; 6,312,304; 6,312,971; 6,323,989; 6,327,072; 6,376,828; 6,377,387; 6,392,785; 6,392,786; 6,413,790; 6,422,687; 6,445,374; 6,445,489; 6,459,418; 6,473,072; 6,480,182; 6,498,114; 6,504,524; 6,506,438; 6,512,354; 6,515,649; 6,518,949; 6,521,489; 6,531,997; 6,535,197; 6,538,801; 6,545,291; and 6,580,545; and U.S. Patent Applications Publication Nos. 2002/0019081; 2002/0021270; 2002/0053900; 2002/0060321; 2002/0063661; 2002/0063677; 2002/0090980; 2002/0106847; 2002/0113770; 2002/0130832; 2002/0131147; 2002/0145792; 2002/0171910; 2002/0180687; 2002/0180688; 2002/0185378; 2003/0011560; 2003/0011867; 2003/0011868; 2003/0020844; 2003/0025855; 2003/0034949; 2003/0038755; 2003/0053189; 2003/0076573; 2003/0096113; 2003/0102858; 2003/0132908; 2003/0137521; 2003/0137717; and 2003/01151702; and International Applications Publication Nos. WO 99/67678; WO 00/05704; WO 00/38000; WO 00/38001; WO

00/36560; WO 00/67110; WO 00/67327; WO 01/07961; and WO 01/08241. All of these patents and applications are in the name of, or assigned to, the Massachusetts Institute of Technology (MIT) or E Ink Corporation.

[0007] Many of the aforementioned patents and applications recognize that the walls surrounding the discrete microcapsules in an encapsulated electrophoretic medium could be replaced by a continuous phase, thus producing a so-called "polymer-dispersed" electrophoretic display in which the electrophoretic medium comprises a plurality of discrete droplets of an electrophoretic fluid and a continuous phase of a polymeric material, and that the discrete droplets of electrophoretic fluid within such a polymer-dispersed electrophoretic display may be regarded as capsules or microcapsules even though no discrete capsule membrane is associated with each individual droplet; see for example, U.S. Patent No. 6,392,786, at column 6, lines 44-63. See also the aforementioned U.S. Patent Application Publication No. 2002/0131147, and the corresponding International Application PCT/US02/06393. Accordingly, for purposes of the present application, such polymer-dispersed electrophoretic media are regarded as sub-species of encapsulated electrophoretic media.

[0008] A related type of electrophoretic display is a so-called "microcell electrophoretic display", sometimes also called a "microcup" electrophoretic display. In a microcell electrophoretic display, the charged particles and the suspending fluid are not encapsulated within microcapsules but instead are retained within a plurality of cavities formed within a carrier medium (or substrate), typically a polymeric film. See, for example, International Applications Publication No. WO 02/01281, and published US Application No. 2002/0075556, both assigned to Sipix Imaging, Inc.

[0009] Hereinafter, the term "microcavity electrophoretic display" will be used to cover both encapsulated and microcell electrophoretic displays.

[0010] One of the problems with electrophoretic displays is the limited range of colors which each pixel of the display can produce. The prior art describes two main types of electrophoretic media. One type comprises a single type of electrically charged particle in a colored medium. This type of medium is only capable of producing two colors at each pixel; either the color of the particles or the color of the medium is

seen. The second type of medium comprises two different types of electrically charged particles in an essentially uncolored medium; the two types of particles may differ in polarity of electric charge or have charges of the same polarity but differ in electrophoretic mobility. Again, this type of medium is only capable of producing two colors at each pixel, namely the colors of the two types of particles.

[0011] One approach to expanding the limited range of colors available from conventional electrophoretic displays is to place an array of colored filters over the pixels of the display. For example, consider the effect on a display comprising white particles in a black fluid of placing an array of color filters (say red, green and blue) over the individual pixels of the display. Moving the white particles adjacent the viewing surface of a pixel covered with a red filter would color that pixel red, whereas moving the white particles of the same pixel adjacent the rear surface of the display would render the pixel black. The main problem with this approach to generating color is that the brightness of the display is limited by the pixelation of the color filter. For example, if a red color is desired, the pixels covered by red filters are set to appear red. whereas the pixels covered by green and blue filters are set to appear dark, so that only a fraction of the display surface has the desired color while the remaining portion is dark, thus limiting the brightness of any color obtained. A reflective display that was capable of three optical states (black, white and color or black, white and transparent) would significant advantages in image quality, cost and ease of manufacture.

[0012] Conventional electrophoretic displays rely upon movement of electrically charged particles in an electric field under electrostatic forces; the particles move along the lines of force of the electric field. However, it is known that objects can be moved by dielectrophoretic forces, that is to say that dipoles induced in the objects by a non-uniform electric field cause the particles to move towards regions of higher field strength. See, for example, U.S. Patent No. 4,418,346 to Batchelder which describes an apparatus for providing a dielectrophoretic display of visual information. In this apparatus, a "bubble" of a fluid is moved through a second, immiscible fluid in a stepwise manner by applying voltages to closely spaced electrodes, the bubble being visible against a visually contrasting background. Visual information is conveyed by the position of the bubble relative to the background. The patent suggests that a

simple one-dimensional display of this type might represent the level of an analog signal by the position of the bubble. However, since the movement involved is that of a bubble against a contrasting background, such an apparatus does not appear capable of displaying an arbitrary image.

[0013] It has now been realized that using a microcavity electrophoretic medium in a dielectrophoretic display greatly simplifies the problem of generating the heterogeneous electric field required by such a display, since differences between the dielectric constant and/or conductivity between the suspending fluid and the material surrounding the suspending fluid (such as a polymeric binder in which the capsules are embedded, as described in many of the aforementioned E Ink and MIT patents and publications, or the substrate in which the cavities of a microcell electrophoretic display are formed) will result in a heterogeneous electric field which can be used to move the particles within the suspending fluid against the side walls of the cavities, thereby providing the display with a substantially transparent state.

SUMMARY OF INVENTION

[0014] Accordingly, this invention provides a dielectrophoretic display comprising:

[0015] a substrate having walls defining at least one cavity, the cavity having a viewing surface and a side wall inclined to the viewing surface;

[0016] a suspending fluid contained within the cavity;

[0017] a plurality of at least one type of particle suspended within the suspending fluid; and

[0018] means for applying to the substrate an electric field effective to cause dielectrophoretic movement of the particles to the side wall of the cavity.

[0019] This invention also provides a process for operating a dielectrophoretic display, the process comprising:

[0020] providing a substrate having walls defining at least one cavity, the cavity having a viewing surface and a side wall inclined to the viewing surface; a suspending fluid contained within the cavity; and a plurality of at least one type of particle suspended within the suspending fluid; and

[0021] applying to the substrate an electric field effective to cause dielectrophoretic movement of the particles to the side wall of the cavity.

[0022] In the dielectrophoretic display of the present invention, the suspending fluid may be substantially uncolored, and have suspended therein only a single type of particle.

[0023] At least some of the at least one type of particle may be electrically charged, and in one form of a display containing such electrically charged particles, the suspending fluid may have suspended therein a first type of particle having a first optical characteristic and a first electrophoretic mobility, and a second type of particle having a second optical characteristic different from the first optical characteristic and a second electrophoretic mobility different from the first electrophoretic mobility. The first and second electrophoretic mobilities may differ in sign, so that the first and second types of particles move in opposed directions in an electric field, and the suspending fluid may be substantially uncolored. This type of display may further comprise a backing member disposed on the opposed side of the cavity from the viewing surface, at least part of the backing member having a third optical characteristic different from the first and second optical characteristics. The backing member may comprise areas having third and fourth optical characteristics different from each other and from the first and second optical characteristics. In preferred forms of such a display, the backing member comprises areas having red, green and blue or yellow, cyan and magenta colors, and the first and second optical characteristics may comprise black and white colors.

[0024] In the dielectrophoretic display of the present invention, the cavity may have a non-circular cross-section, preferably a polygonal cross-section, as seen from the viewing surface. The at least one type of particle may be formed from an electrically conductive material, for example a metal, carbon black or a doped semiconductor.

[0025] As already indicated, in the dielectrophoretic display of the present invention, the substrate may comprises at least one capsule wall (typically a deformable wall) so that the dielectrophoretic display comprises at least one capsule. For reasons explained in the aforementioned 2003/0137717, the capsules are preferably arranged in a single layer. Alternatively, the substrate may comprise a continuous phase surrounding a plurality of discrete droplets of the suspending fluid having the at least one type of

particle suspended therein (i.e., the display may be of the polymer-dispersed type), or may comprises a substantially rigid material having the at least one cavity formed therein, the substrate further comprising at least one cover member closing the at least one cavity, so that the display is of the microcell type.

[0026] In the process of the present invention, the electric field may be an alternating electric field. When the display is of the type in which at least some of the at least one type of particle are electrically charged, and the suspending fluid has suspended therein a first type of particle having a first optical characteristic and a first electrophoretic mobility, and a second type of particle having a second optical characteristic different from the first optical characteristic and a second electrophoretic mobility different from the first electrophoretic mobility, with the first and second electrophoretic mobilities differing in sign, so that the first and second types of particles move in opposed directions in an electric field, the process may further comprise:

[0027] applying an electric field of a first polarity to the cavity, thereby causing the first type of particles to approach the viewing surface and the cavity to display the first optical characteristic at the viewing surface; and

[0028] applying an electric field of a polarity opposite to the first polarity to the cavity, thereby causing the second type of particles to approach the viewing surface and the cavity to display the second optical characteristic at the viewing surface.

BRIEF DESCRIPTION OF DRAWINGS

[0029] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

[0030] Figure 1 of the accompanying drawings is a schematic section showing a white opaque state of a dielectrophoretic display of the present invention.

[0031] Figure 2 is a schematic section similar to Figure 1 but showing a black opaque state of the display shown in Figure 1.

[0032] Figure 3 is a schematic section similar to Figures 1 and 2 but showing a transparent state of the display shown in Figures 1 and 2.

[0033] Figures 4 to 6 are top plan views through the viewing surface of an experimental display in the states corresponding to Figures 1 to 3 respectively.

[0034] Figures 7 and 8 illustrate the transition from the white optical state of the display shown in Figure 4 to the transparent state shown in Figure 6.

[0035] Figures 9 to 11 are schematic sections through a microcell display of the present invention in states corresponding to those of Figures 1 to 3 respectively.

DETAILED DESCRIPTION

[0036] As already mentioned, this invention provides a dielectrophoretic display comprising a substrate having walls defining at least one cavity, the cavity having a viewing surface and a side wall inclined to the viewing surface; a suspending fluid contained within the cavity; a plurality of at least one type of particle suspended within the suspending fluid; and means for applying to the substrate an electric field effective to cause dielectrophoretic movement of the particles to the side wall of the cavity.

[0037] References to "viewing surface" and "side wall" herein do not imply that these surfaces are perpendicular to each other, though a substantially perpendicular arrangement of the two surfaces is preferred, since when the particles are disposed adjacent the side wall of the cavity, such a perpendicular arrangement minimizes the area of the viewing surface occupied by the particles, and hence permits the maximum amount of light to pass through the cavity. The side wall or walls of the cavity also need not be planar; for example, an encapsulated display of the present invention may use capsules as described in the aforementioned U.S. Patent No. 6,067,185 having the form of "flattened spheres" (i.e., oblate ellipsoids) with curved side walls.

[0038] In this display, it is necessary that there be a difference between the dielectric constant and/or conductivity of the suspending fluid and that of the substrate to provide the heterogeneous electric field necessary for dielectrophoresis. Desirably, this difference should be made as large as possible. It may also be advantageous to use a capsule which has a non-circular, and preferably polygonal, cross-section perpendicular to the direction of the applied electric field since sharply curved regions or corners of the capsule produce increased field heterogeneity and thus assist the dielectrophoretic movement of the particles.

[0039] Those skilled in the technology of electrophoretic displays will appreciate that both electrically neutral and electrically charged particles can be moved by dielectrophoresis, since dielectrophoretic movement is dependent upon dipoles induced in the particles by the electric field and not upon any pre-existing charge on the particles. However, it appears advantageous to use electrically charged particles in the apparatus and process of the present invention since once the particles have been moved to the side wall of the capsule by dielectrophoresis, it appears desirable to use normal electrophoretic movement of the particles to disperse them; it will be appreciated that since the heterogeneity of the electric field in an encapsulated display is due to differences between the properties of the suspending fluid on the one hand and the capsule wall and surrounding material on the other, there will normally be no way of reversing the high field and low field regions in a manner similar to that used in the Batchelder apparatus, so that if the particle movement caused by dielectrophoresis is to be reversed, some applied force other than dielectrophoresis must be used.

[0040] If electrically charged particles are used in the present apparatus and process, the particles are of course subject to both electrophoretic and dielectrophoretic forces when an electric field is applied. Typically, electrophoretic movement of particles will be much more rapid than dielectrophoretic, so that to ensure that the desired dielectrophoretic movement is not subject to interference from electrophoretic movement, it is desirable to reverse the electric field at intervals; provided the field is applied for the same amount time in each direction, the electrophoretic movements will sum to zero, since electrophoretic movement is polarity-sensitive, whereas the dielectrophoretic movements will not sum to zero since dielectrophoretic movement is polarity-independent.

[0041] The dielectrophoretic movement of the particles in the apparatus and process of the present invention is affected by the material from which the particles are formed, and the size and shape of the particles. Since dielectrophoresis depends upon the induction of dipoles within the particles, it is desirable to use particles which are highly polarizable, especially conductive particles such as metals. For example, aluminum particles may be used in the present invention. It has been observed experimentally that carbon black particles, which have a reasonably high conductivity,

have substantially greater dielectrophoretic mobility than substantially non-conductive titania particles. The particles may also be formed from a doped semiconductor; the type of doping is not critical provided that the particles have sufficient conductivity, but most undoped semiconductors have too low a conductivity to have high dielectrophoretic mobility.

[0042] The induced dipole, and hence the dielectrophoretic movement of the particles, is also affected by the size and shape of the particles. Since a large particle allows greater separation between the poles of a dipole than a smaller particle, increasing the size of the particles will increase dielectrophoretic mobility, although of course the particles should not be made so large as to readily visible when they lie adjacent the side wall of the capsule. For similar reasons, elongate particles, especially needle-shaped particles, will tend to have a higher dielectrophoretic mobility than spherical particles of the same volume. Anisotropically shaped particles may also be useful in the present invention.

[0043] There are two main variations of the apparatus and process of the present invention. In the first variation, the cavity contains only a single type of particle in an uncolored suspending fluid. This capsule can be switched between an "opaque" state, in which the particles are dispersed throughout the suspending fluid, and a "transparent" state, in which the particles are moved to a side wall of the capsule so that light can pass through the uncolored suspending fluid. The transparent state need not appear transparent to a viewer; as illustrated in the drawings and as described in more detail below, a reflector or filter having a color different from that of the particles may be placed on the opposed side of the capsule from the viewing surface thereof, so that in the transparent state a viewer sees the color of the reflector or filter; in the opaque state the color of the reflector or filter is of course hidden by the dispersed particles.

[0044] In the second variation, the capsules contain two different types of particles differing in at least one optical characteristic and in electrophoretic mobility and a suspending fluid which may be colored or uncolored. This capsule can be switched among three states, namely a first opaque state, in which the first type of particles are visible, a second opaque state, in which the second type of particles are visible, and a "transparent" state, in which both types of particles are moved to a side wall of the capsule by dielectrophoresis and the color of the suspending fluid is visible; if, as will

typically be the case, the suspending fluid is uncolored, the transparent state is actually transparent and may be used to display the color of a reflector or filter disposed on the opposed side of the capsule from the viewing surface thereof, as previously described.

[0045] It will be appreciated that, provided that the desired color can be seen when a display of the present invention is in a transparent state, the location of the colored material is essentially irrelevant. Thus, although reference has been made above to a reflector or filter, it is not essential that this reflector or filter be a discrete integer, and color could be provided in any convenient location. Thus, for example, the colored reflector or filter could be provided by coloring (a) the substrate itself, for example the polymeric film used in a microcell form of the present display; (b) a material associated with the substrate, for example a polymeric binder used to retain capsules in a coherent layer in an encapsulated display of the invention, or a lamination adhesive layer used to secure the dielectrophoretic layer to a backplane; or (c) the pixel electrodes or another component of a backplane used to drive the display. In principle, in an encapsulated display color could be provided by dyeing the capsule walls themselves, but this does have the disadvantage that in an opaque state of a pixel the color in the portion of the capsule adjacent the viewing surface will affect the color seen at that surface when the pixel is in an opaque state. In some cases, the resultant color shift may be acceptable, or may be minimized, for example by using particles which have a color complementary to that of the color caused by the capsule wall. In other cases, color may be provided only on the parts of the capsule wall lying on the opposed side of the capsule to the viewing surface, for example by providing a radiation-sensitive color-forming material in the capsule wall and then exposing this color-forming material to radiation effective to bring about the formation of color, this radiation being directed on to the capsule from the side of the display opposite to the viewing surface.

[0046] Color could also be provided from a source separate from the display itself. For example, if a display of the present invention is arranged to operate as a light valve and backlit by projecting light on to a surface on the opposed side of the display from the viewing surface, color could be provided by imaging an appropriate color filter on to the rear surface of the display.

[0047] Except in cases where it is essential that the colored member be light transmissive, the color may be provided either by dyes or pigments, although the latter are generally preferred since they are typically more stable against prolonged exposure to radiation, and thus tend to provide displays with longer operating lifetimes.

[0048] As already indicated, no special electrode configurations are required in the display and process of the present invention; the invention can be practiced with simple parallel electrodes on opposed sides of the cavity; for example, a multi-pixel display of the invention using at least one cavity per pixel could have the conventional electrode configuration of a single pixel electrode for each pixel on one side of the cavities and a single common electrode extending across all the pixels on the opposed side of the cavities. However, this invention does not exclude the possibility that the electrodes might be shaped to enhance the dielectrophoretic effect. It may also be useful to use so-called "z-axis adhesives" (i.e., adhesives having a substantially greater conductivity parallel to the thickness of a layer of adhesive than in the plane of this layer) between one or both of the electrodes and the cavities cf. copending Application Serial No. 60/319,934, filed February 11, 2003, the entire disclosure of which is herein incorporated by reference. In addition, as discussed in detail below with reference to the drawings, in some embodiments of the invention it may be advantageous to provide auxiliary electrodes to assist in redispersing the particles in the suspending fluid after the particles have be driven to the side walls by dielectrophoresis.

[0049] As already mentioned, there are three principal types of dielectrophoretic displays of the present invention. The first type is the "classical" encapsulated electrophoretic type as described in the aforementioned E Ink and MIT patents and applications. In this type of display, the substrate has the form of at least one capsule wall, which is typically deformable, and formed by depositing a film-forming material around a droplet containing the suspending fluid and the dielectrophoretic particles. The second type is the polymer-dispersed electrophoretic type in which the substrate comprises a continuous phase surrounding a plurality of discrete droplets of the suspending fluid. Full details regarding the preparation of this type of display are given in the aforementioned 2002/0131147. The third type is the microcell display, in which a plurality of cavities or recesses are formed in a substrate, filled with the

suspending fluid and particles and then sealed, either by lamination a cover sheet over the recesses or by polymerizing a polymerizable species also present in the suspending fluid.

[0050] The first dielectrophoretic display (generally designed 100) of the invention shown in Figures 1 to 3 comprises an encapsulated dielectrophoretic medium (generally designated 102) comprising a plurality of capsules 104 (only one of which is shown in Figures 1 to 3), each of which contains a suspending liquid 106 and dispersed therein a plurality of a first type of particle 108, which for purposes of illustration will be assumed to be black. The particles 108 are electrophoretically mobile and may be formed of carbon black. In the following description, it will be assumed that the particles 108 are positively charged, although of course negatively charged particles could also be used if desired. Also suspended in the suspending liquid 106 is a plurality of a second type of particle 110, which is electrophoretically mobile and negatively charged, and may be formed of titania. (The triangular shape of the particles 108, and the circular shape of the particles 110 are used purely to way of illustration to enable the various types of particles to be distinguished easily in the accompanying drawings, and in no way correspond to the physical forms of the actual particles, which are typically substantially spherical. However, we do not exclude the use of non-spherical particles in the present displays.) The display 100 further comprises a common, transparent front electrode 112, which forms a viewing surface through which an observer views the display 100, and a plurality of discrete rear electrodes 114, each of which defines one pixel of the display 100 (only one rear electrode 114 is shown in Figures 1 to 3). (The front electrode 112 is typically provided on a support member which also provides mechanical protection for the display 100 but for simplicity this support member is omitted from Figures 1 to 3.) For ease of illustration and comprehension, Figures 1 to 3 show only a single microcapsule forming the pixel defined by rear electrode 114, although in practice a large number (20 or more) microcapsules are normally used for each pixel. The rear electrodes 114 are mounted upon a substrate 116, which contains areas of differing color, as described in more detail below with reference to Figures 4 to 8.

[0051] Typically the liquid 106 is uncolored (i.e., essentially transparent), although some color may be present therein to adjust the optical properties of the various states of

the display. Figure 1 shows the display 100 with the front electrode 112 positively charged relative to the rear electrode 114 of the illustrated pixel. The positively charged particles 108 are held electrostatically adjacent the rear electrode 114, while the negatively charged particles 110 are held electrostatically against the front electrode 112. Accordingly, an observer viewing the display 100 through the front electrode 112 sees a white pixel, since the white particles 110 are visible and hide the black particles 108.

[0052] Figure 2 shows the display 100 with the front electrode 112 negatively charged relative to the rear electrode 114 of the illustrated pixel. The positively charged particles 108 are now electrostatically attracted to the negative front electrode 112, while the negatively charged particles 110 are electrostatically attracted to the positive rear electrode 114. Accordingly, the particles 108 move adjacent the front electrode 112, and the pixel displays the black color of the particles 108, which hide the white particles 110.

[0053] Figure 3 shows the display 100 after application of an alternating electric field between the front and rear electrodes 112 and 114 respectively. The application of the alternating electric field causes dielectrophoretic movement of both types of particles 108 and 110 to the side walls of the capsule 104, thus leaving the major portion of the area of the capsule 104 essentially transparent. Accordingly, the pixel displays the color of the substrate 116.

[0054] To redisperse the particles 108 and 110 uniformly throughout the suspending liquid 106 from their positions shown in Figure 3, a series of short direct current voltages of alternating polarity is applied between the front and rear electrodes 112 and 114, thereby causing the particles 108 and 110 to oscillate within the suspending liquid 106; this oscillation causes the particles 108 and 110 to gradually redisperse throughout the liquid 106. Application of a longer direct current pulse of appropriate polarity will then cause the pixel to assume the state shown in Figure 1 or 2 depending upon the polarity of the longer pulse.

[0055] In Figures 1 to 3, the capsules 104 are illustrated as being of substantially prismatic form, having a width (parallel to the planes of the electrodes) significantly greater than their height (perpendicular to these planes). This prismatic shape of the capsules

104 is deliberate since it provides the capsules with side walls which extend essentially perpendicular to the viewing surface of the display, thus minimizing the proportion of the area of the capsule 104 which is occupied by the particles 108 and 110 in the transparent state shown in Figure 3. Also, if the capsules 104 were essentially spherical, in the black state shown in Figure 2, the particles 108 would tend to gather in the highest part of the capsule, in a limited area centered directly above the center of the capsule. The color seen by the observer would then be essentially the average of this central black area and a white or colored annulus surrounding this central area, where either the white particles 110 or the substrate 116 would be visible. Thus, even in this supposedly black state, the observer would see a grayish color rather than a pure black, and the contrast between the two extreme optical states of the pixel would be correspondingly limited. In contrast, with the prismatic form of microcapsule shown in Figures 1 and 2, the particles 108 cover essentially the entire cross-section of the capsule so that no, or at least very little, white or other colored area is visible, and the contrast between the extreme optical states of the capsule is enhanced. For further discussion on this point, and on the desirability of achieving close-packing of the capsules within the electrophoretic layer, the reader is referred to the aforementioned U.S. Patent No. 6,067,185. Also, as described in the aforementioned E Ink and MIT patents and applications, to provide mechanical integrity to the dielectrophoretic medium, the capsules 104 are normally embedded within a solid binder, but this binder is omitted from Figures 1 to 3 for ease of illustration.

[0056] Figures 4, 5 and 6 of the accompanying drawings illustrate the white opaque, black opaque and transparent optical states of an experimental display of the present invention substantially as described above with reference to Figures 1 to 3 and comprising a plurality of capsules, each of which contains carbon black and white titania particles bearing charges of opposite polarity in a colorless suspending fluid. The display was prepared substantially as described in the aforementioned 2003/0137717 by encapsulating a hydrocarbon suspending fluid containing the carbon black and titania particles in a gelatin/acacia capsule wall, mixing the resultant capsules with a polymeric binder, coating the capsule/binder mixture on to an indium tin oxide (ITO) coated surface of a polymeric film to provide a single layer of capsules covering the film, and laminating the resultant film to a backplane. For purposes of

illustration, the display shown in Figures 4, 5 and 6 was formed as a single pixel with the transparent front electrode forming the viewing surface of the display, and the backplane (actually a single rear electrode) disposed adjacent a multicolored reflector.

[0057] Figure 4 shows the display in its first, white opaque state corresponding to that of Figure 1, with the white particles moved by electrophoresis and lying adjacent the viewing surface of the display, so that the white particles hide both the black particles and the multicolored reflector, and the display appears white. Similarly, Figure 5 shows the display in its second, black opaque state corresponding to that of Figure 2, with the black particles moved by electrophoresis and lying adjacent the viewing surface of the display, so that the black particles hide both the white particles and the multicolored reflector, and the display appears black. Figure 6 shows the display in a transparent state corresponding to that of Figure 3 caused by applying a square wave with a frequency of 60 Hz and an amplitude of 90V until no further change was visible in the display (approximately 150 seconds). The application of this square wave caused both the black and white particles to move dielectrophoretically to the side walls of the capsules, thus causing the multicolored reflector to be visible through the uncolored suspending fluid. Thus, a display of the type shown in Figures 1 to 6 can display three different colors, which eases the problems of building a full color electro-optic display.

[0058] Figures 7 and 8 illustrate the transition from the white opaque state shown in Figure 4 to the transparent state shown in Figure 6; Figure 7 shows the display after application of the aforementioned square wave for 10 seconds, while Figure 8 shows the display after application of the square wave for 30 seconds. It will be seen from Figures 6, 7 and 8 that development of the transparent state occurs gradually as more and more particles are moved to the side walls of the capsules. In Figure 7, the multicolored reflector is just becoming visible, while in Figure 8 this reflector is more visible but much less clear than in the final transparent state shown in Figure 6.

[0059] Figures 9 to 11 show schematic sections, similar to those of Figures 1 to 3 respectively, of one pixel of a microcell display (generally designated 900) of the present invention. The microcell display 900 uses essentially the same dielectrophoretic medium, comprising a suspending liquid 106 with carbon black particles 108 and white titania particles suspended therein, as the encapsulated

display 100 shown in Figures 1 to 3; however, the form of substrate used in the display 900 differs substantially from that of the display 100. In the display 900, the substrate comprises a base member 120 and a plurality of side walls 122 extending perpendicular to the base member 120 and forming a plurality of microcells in which are confined the liquid 106 and the particles 108 and 110. The lower faces (as illustrated in Figures 9 to 11) of the microcells are closed by closure walls 124, which are formed by radiation polymerization of a polymerizable species originally present in the liquid 106; see the aforementioned International Application Publication No. WO 02/01281, and published US Application No. 2002/0075556. The display 900 further comprises a front electrode 112, a rear or pixel electrode 114 and a colored substrate 116 all of which are essentially identical to the corresponding integers in Figure 1. (In the same way as in Figures 1 to 3, for simplicity Figures 9 to 11 are drawn as if there is only a single microcell to the pixel defined by the electrode 114 although in practice a single pixel may comprise multiple microcells.) The display 900 also comprises auxiliary electrodes embedded within the side walls 122 and a protective layer 126 covering the front electrode 112.

[0060] As shown in Figures 9 to 11, the microcell display 900 operates in a manner very similar to the encapsulated display 100 shown in Figures 1 to 3. Figure 9 shows the display 900 with the front electrode 112 positively charged relative to the rear electrode 114 of the illustrated pixel. The positively charged particles 108 are held electrostatically adjacent the rear electrode 114, while the negatively charged particles 110 are held electrostatically against the front electrode 112. Accordingly, an observer viewing the display 100 through the front electrode 112 sees a white pixel, since the white particles 110 are visible and hide the black particles 108.

[0061] Figure 10 shows the display 900 with the front electrode 112 negatively charged relative to the rear electrode 114 of the illustrated pixel. The positively charged particles 108 are now electrostatically attracted to the negative front electrode 112, while the negatively charged particles 110 are electrostatically attracted to the positive rear electrode 114. Accordingly, the particles 108 move adjacent the front electrode 112, and the pixel displays the black color of the particles 108, which hide the white particles 110.

[0062] Figure 11 shows the display 900 after application of an alternating electric field

between the front and rear electrodes 112 and 114 respectively. The application of the alternating electric field causes dielectrophoretic movement of both types of particles 108 and 110 to the side walls of the microcell, thus leaving the major portion of the area of the microcell essentially transparent. Accordingly, the pixel displays the color of the substrate 116.

[0063] Redispersion of the particles 108 and 110 from the transparent state of the display 900 shown in Figure 11 may be effected in the same way as described above for the display 100. However, the auxiliary electrodes 126 are provided to assist in such redispersion. The auxiliary electrodes run the full width of the display (which is assumed to be perpendicular to the plane of Figures 9 to 11), i.e., each auxiliary electrode is associated with a full row of microcells, and the auxiliary electrodes are connected to a voltage source which, when activated, applies voltages of opposed polarities to alternate auxiliary electrodes 126. By applying a series of voltage pulses of alternating polarity to the auxiliary electrodes 126, an electric field is created in the left-right direction in Figures 9 to 11, which greatly assists is redispersing all the particles 108 and 110 throughout the display uniformly within the liquid 106. Voltage pulses of alternating polarity may also be applied to the electrodes 112 and 114 as previously described to further assist in redispersing the particles 108 and 110.

[0064] It will be appreciated that the present invention need not make use of a colored reflector behind the capsules but may be used to provide backlit displays, variable transmission windows and transparent displays; indeed, the present invention may be useful in any where light modulation is desired..

[0065] Those skilled in the display art will appreciate that numerous changes, improvements and modifications can be made in the preferred embodiments of the invention already described without departing from the scope of the invention. Accordingly, the whole of the foregoing description is intended to be construed in an illustrative and not in a limitative sense.